Department I - C Plus Plus

Modern and Lucid C++
for Professional Programmers

Week 7 – Standard Containers & Iterators

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HS2023

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Goals

- **You know the properties of the different standard containers**
- **You can select the best standard containers for your application**
- **You know the different iterator categories and their capabilities**
- **You can explain the difference between a const iterator and a const_iterator**

Topics

- **Recap Week 6**
- **Standard Containers**
  - Common API
  - Sequence Containers
  - Associative Containers
  - Hashed Containers
- **Iterators (Continued)**

Recap Week 6

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- **Which + operator would be valid for the call in `main()`?**

```
namespace quiz {
  struct Point {
    int x; int y;

    auto operator+(Point const& other) const -> Point;
  };

  auto operator+(Point const& l, Point const& r) -> Point;
} //namespace quiz

auto operator+(quiz::Point const& l, quiz::Point const& r) -> quiz::Point;

auto main() -> int {
  quiz::Point p1{1, 2};
  quiz::Point p2{3, 4};
  p1 + p2;
}
```

- **Which conversions require a `static_cast`?**

```
enum class TrafficLight {
  Off, Green, Yellow, Red
};

auto toggle(TrafficLight& light) -> void {
  if (light == 0) {
    return;
  }
  int value = light % TrafficLight::Red;
  light = value + 1;
}
```

STL Containers: General API

Goals:

- You know the different standard containers categories
- You know the properties of the categories
- You know common functionality of most standard containers

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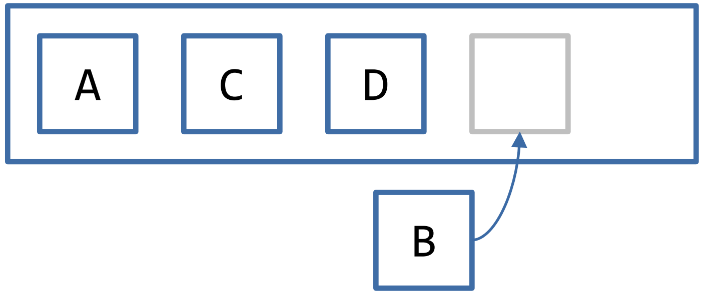
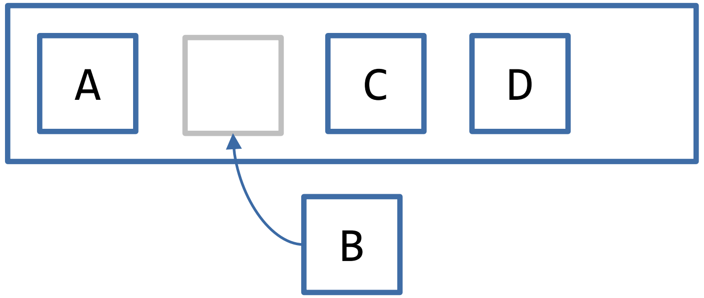
Categories of STL Containers

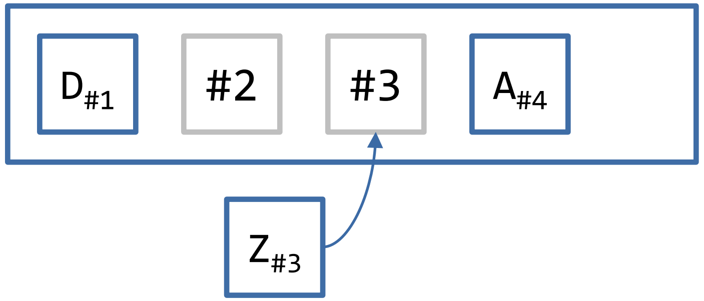
- **Sequence Containers**
  - Elements are accessible in order as they were inserted/created
  - Find in linear time through the algorithm find

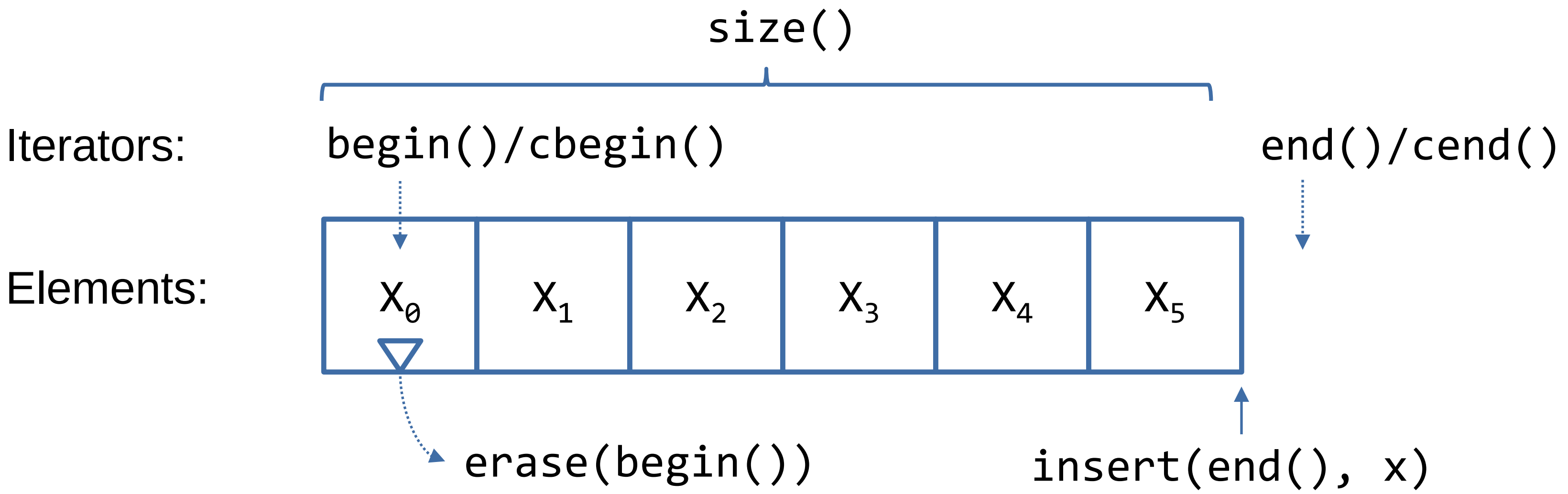


- **Associative Containers**
  - Elements are accessible in sorted order
  - `find` as member function in logarithmic time



- **Hashed Containers (Unordered Associative)**
  - Elements are accessible in unspecified order
  - `find` as member function in constant time





- **All containers have the same/a similar basic interface**

Member Function	Purpose
`begin()` `end()`	Get iterators for algorithms and iteration in general
`erase(iter)`	Removes the element at position the iterator `iter` points to
`insert(iter, value)`	Inserts `value` at the position the iterator `iter` points to
`size()` `empty()`	Check the size of the container

- **Containers can be...**
  - ... default-constructed
  - ... copy-constructed from another container of the same type
  - ... equality compared if they are of the same type
    (or even lexicographically compared with relational operators)
    as long as their elements can be compared accordingly
  - ... emptied with `clear()`

```
std::vector<int> v{};
std::vector<int> vv{v};
if (v == vv) {
  v.clear();
}
```

- **Construction with initializer list**

```
std::vector<int> v{1, 2, 3, 5, 7, 11};
```

v: | 1 | 2 | 3 | 5 | 7 | 11 |

- **Construction with a number of elements**
  - Can provide default value
  - Often needs parenthesis instead of { } to avoid ambiguity from list of values initialization

```
std::list<int> l(5, 42);
```

l: 42 ↔ 42 ↔ 42 ↔ 42 ↔ 42

- **Construction from a range given by a pair of iterators**
  - might need parenthesis instead of {} (rare)

```
std::deque<int> q{cbegin(v), cend(v)};
```

q: | 1 | 2 | 3 | 5 | 7 | 11 |

Sequence Containers

Goals:

- You know the sequence containers of the standard library
- You know the capabilities of the individual sequence containers

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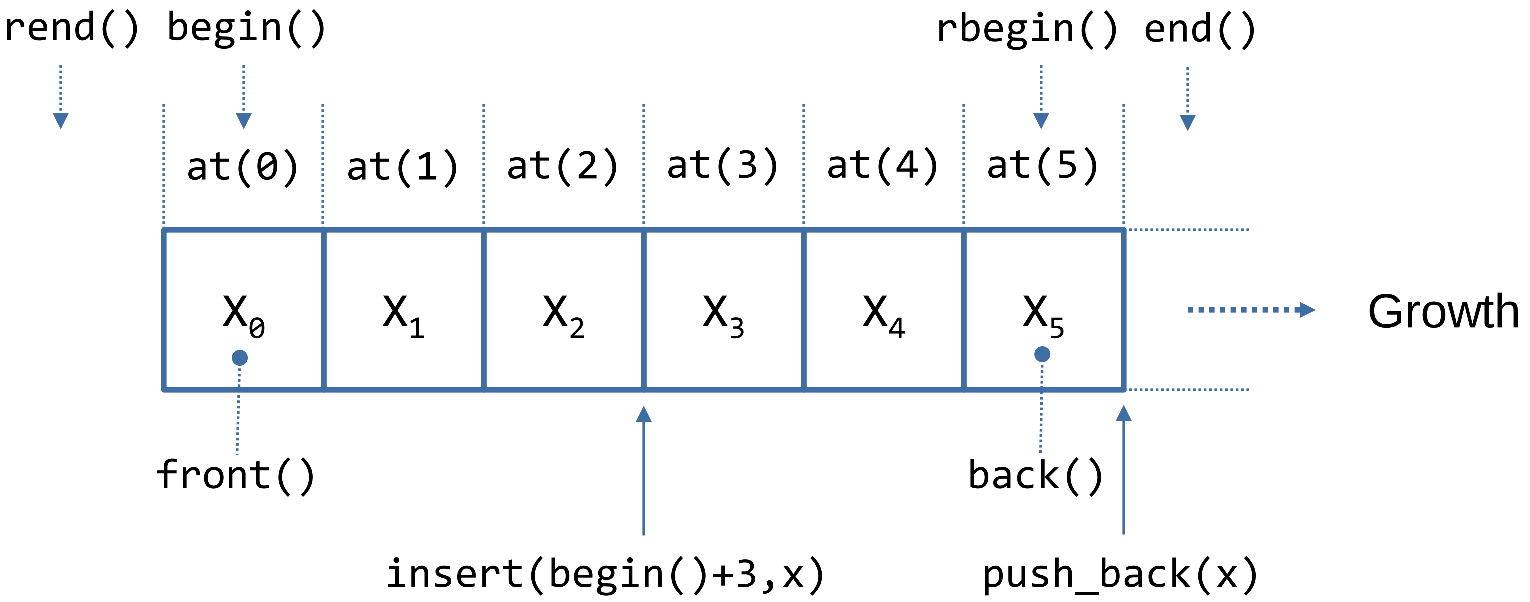
Sequence Containers: `std::vector` & Co.

`std::vector<T>   std::deque<T>   std::list<T>   std::array<N, T>`

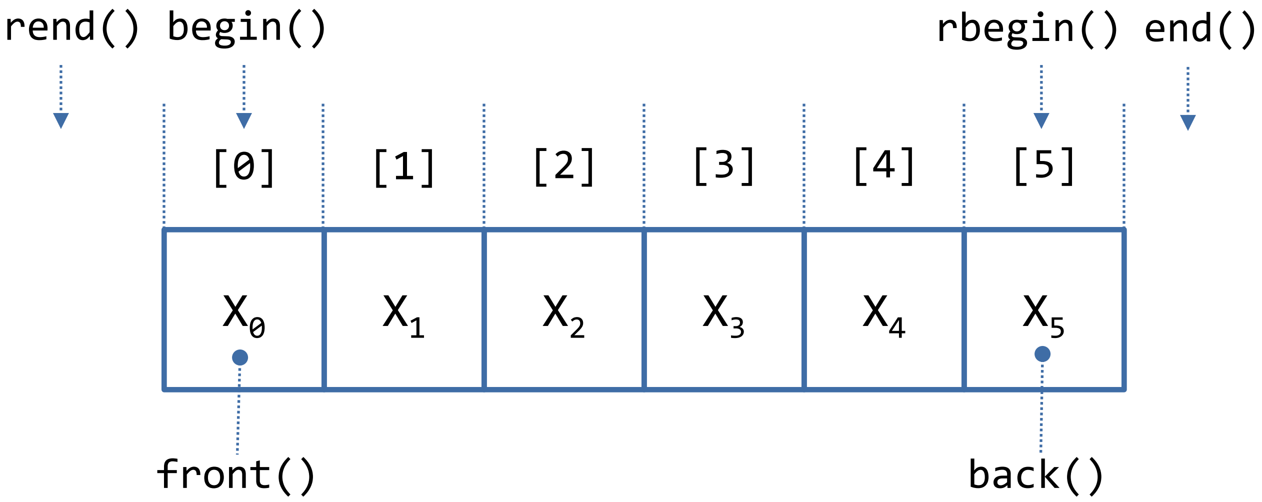


- **Define order of elements as inserted/appended**
- **Lists are good for splicing and in the middle insertions**
- **`std::vector/std::deque` are efficient unless bad usage**

Special Case: `std::array`

`#include <array>`


```
std::array values{1, 1, 2, 3, 5, 8};
```



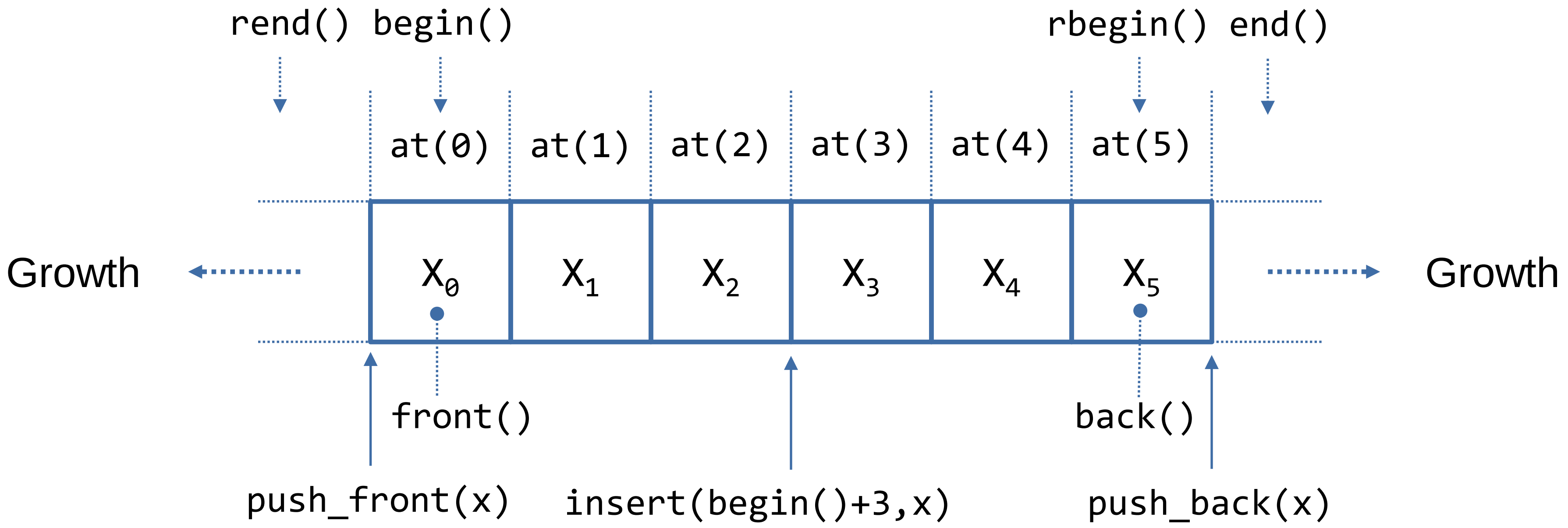
- **Fixed-size "container", cannot insert/append**
- **Can be initialized at compile-time**
- **Use `std::array` instead of C-style arrays when defining arrays**

```
int obsolete[]{1, 1, 2, 3, 5, 8};
```

Double-Ended Queue: `std::deque<T>`

`#include <deque>`

```
std::deque<int> q{begin(v), end(v)};
q.push_front(42);
q.pop_back();
```

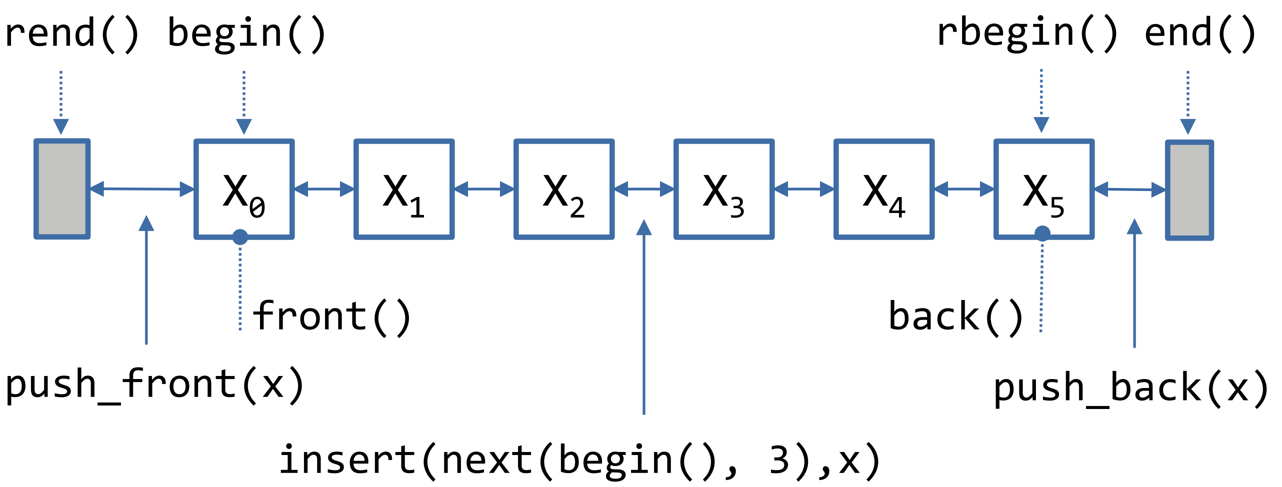


- **`std:deque` is like `std::vector` but with additional, efficient front insertion/removal**
  - `push_front()` and `pop_front()`
- **Special implementation for `bool`: `std::vector<bool>` and `std::deque<bool>`**

Double-Linked List: `std::list<T>`

`#include <list>`


```
std::list<int> l(5, 1);
```

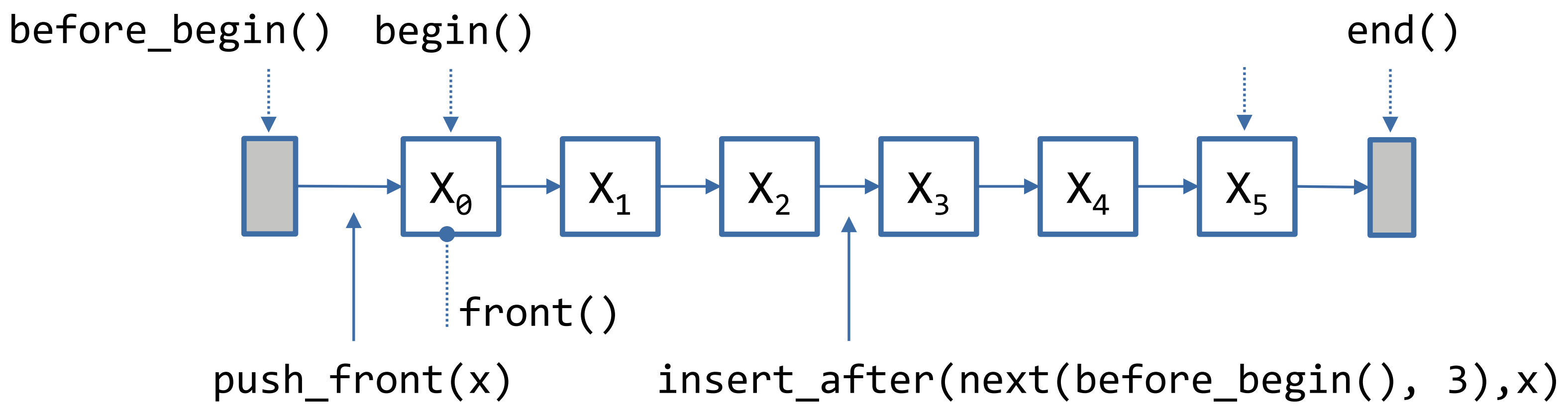


- **Efficient insertion in any position**
- **Lower efficiency in bulk operations**
- **Requires member-function call for `sort()` etc.**
- **Only bi-directional iterators – no index access!**

Singly-Linked List: `std::forward_list<T>`

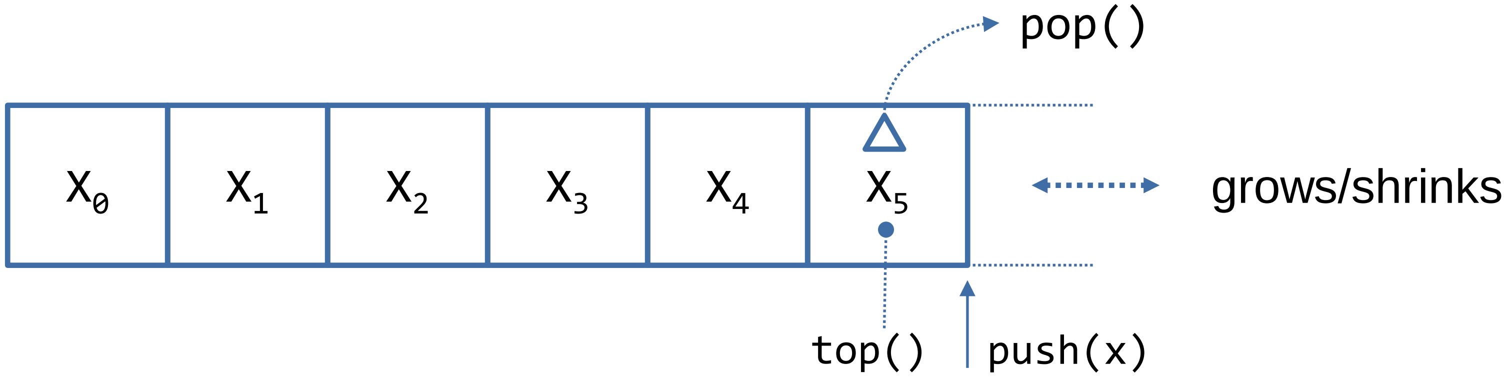
`#include <forward_list>`

```
std::forward_list<int> l{1, 2, 3, 4, 5, 6};
```



- **Efficient insertion AFTER any position, but clumsy with iterator to get "before" position**
- **Only forward-iterators, clumsy to search and remove, use member-functions not algorithms**
- **Avoid, except when there is a specific need! Better use `std::list` or even better `std::vector`**

```cpp
std::stack<int> s{};
s.push(42);
std::cout << s.top();
s.pop();
```

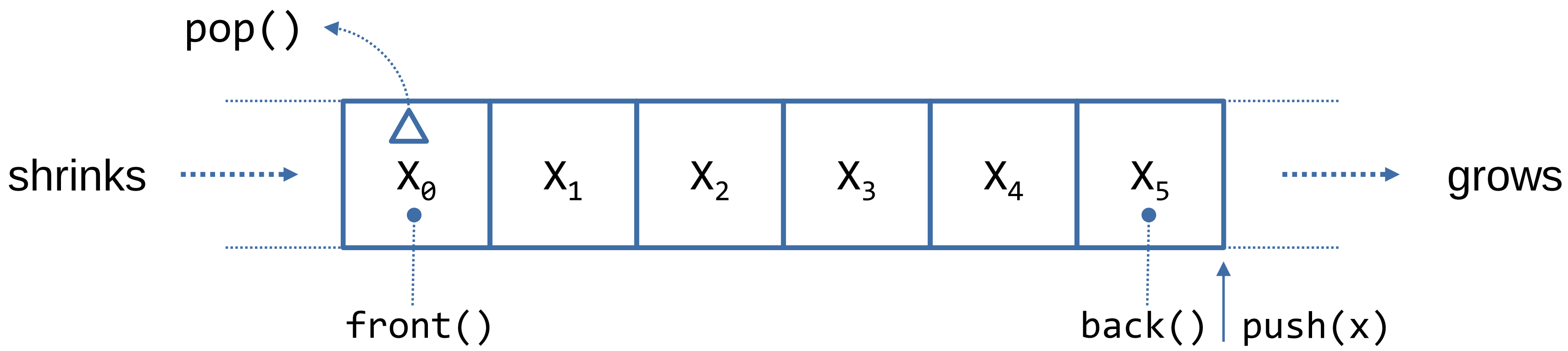


- **Uses `std::deque` (or `std::vector`, `std::list`) and limits its functionality to stack operations**
  - Delegates to `push_back()`, `back()` and `pop_back()`
  - Iteration not possible
- **No longer a container, deliberate limitation!**

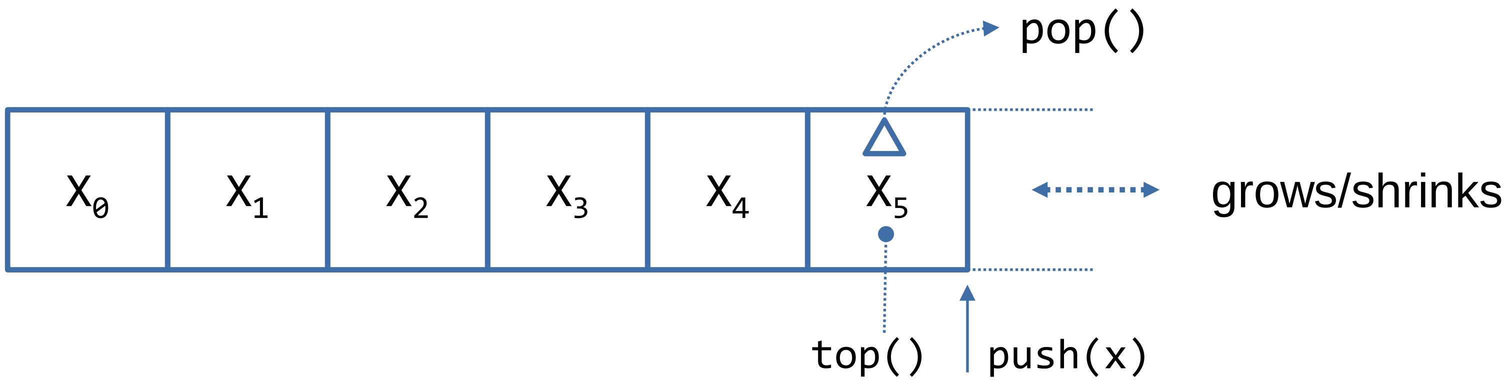
FIFO Adapter: std::queue

#include <queue>

```cpp
std::queue<int> q{};
q.push(42);
std::cout << q.front();
q.pop();
```



- **Uses std::deque (or std::list) and limits its functionality to queue operations**
  - Delegates to push_back() and pop_front()
  - Iteration not possible
- **No longer a container, deliberate limitation!**



- **Uses `std::deque` (or `std::vector`) and limits its functionality to stack operations**
  - But keeps elements partially sorted as (binary) heap
- **`top()` element is always the smallest (requires element type to be comparable)**
- **No longer a container, deliberate limitation!**

```cpp
#include <iostream>
#include <queue>
#include <stack>
#include <string>

auto main() -> int {
  std::stack<std::string> lifo{};
  std::queue<std::string> fifo{};
  for (std::string s : { "Fall", "leaves", "after", "leaves", "fall" }) {
    lifo.push(s);
    fifo.push(s);
  }
  while (!lifo.empty()) { // fall leaves after leaves Fall
    std::cout << lifo.top() << ' ';
    lifo.pop();
  }
  std::cout << '\n';
  while (!fifo.empty()) {// Fall leaves after leaves fall
    std::cout << fifo.front() << ' ';
    fifo.pop();
  }
}
```

?

```cpp
#include <algorithm>
#include <list>
#include <stdexcept>

auto median(std::list<int>& values) -> int {
  if (values.empty()) {
    throw std::invalid_argument{"empty..."};
  }
  sort(begin(values), end(values));
  return values[values.size() / 2];
}
```

Incorrect

`std::list` provides its own sort member function because it does not have random access iterators (see later in this lecture)
`values.sort();`

`std::list` does not provide index access operators

```cpp
#include <queue>
#include <string>

using SplitFlapDisplay =
                      std::queue<std::string>;

auto flip(SplitFlapDisplay& display) -> void {
  display.push(display.front());
  display.pop();
}
```

Correct

The `std::queue` features `push` and `pop` for modification. However, `pop` does not return the popped element. It has to be querried with `front`.

This implies a copy. In C++ Advanced we will look at how to make this more efficient.

Associative Containers

Goals:

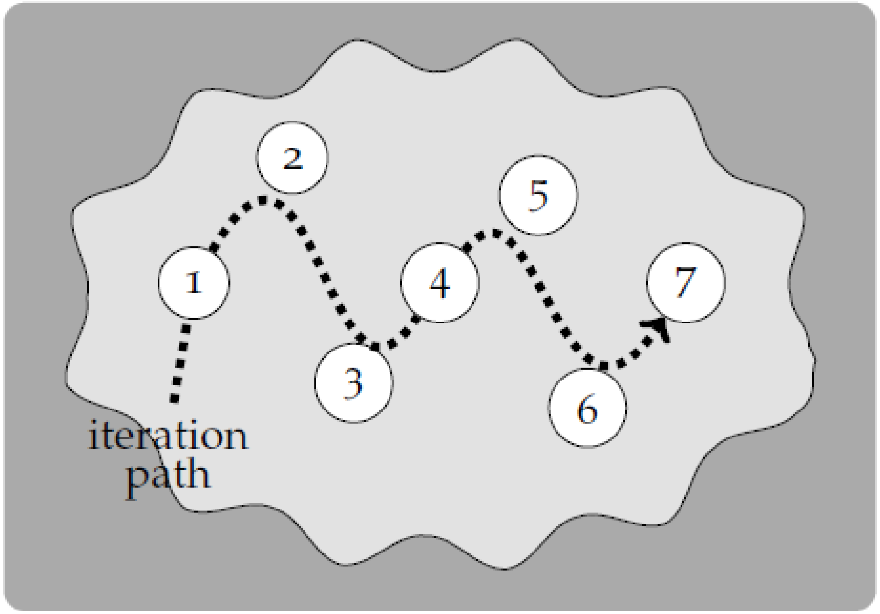
- You know the associative containers of the standard library
- You know the capabilities of the individual associative containers

- **Allow searching by content, not by sequence**
  - Search by key
  - Access key or key-value pair
- **Better name: "Sorted Associative Containers"**
- **Properties**

	Key Only	Key-Value Pair
Key Unique	`std::set<T>`	`std::map<K, V>`
Multiple Equivalent Keys	`std::multiset<T>`	`std::multimap<K, V>`

```
std::set<int> values{7, 1, 4, 3, 2, 5, 6};
```

- **Stores elements in sorted order (ascending by default)**
  - Order can be overwritten by the 2nd template parameter
- **Iteration walks over the elements in order**
  - Keys cannot be modified through iterators!
- **Use member functions for `.find` and `.count`**
  - Tree-search instead of sequential search
  - Result of `.count(element)` is either `0` or `1`
  - Since C++20 there is a `.contains(element)` member



```
#include <iostream>
#include <set>

auto filterVowels(std::istream& in, std::ostream& out) -> void {
  std::set const vowels{'a', 'e', 'o', 'u', 'i', 'y'};
  char c{};
  while (in >> c) {
    if (!vowels.contains(c)) {
      out << c;
    }
  }
}
auto main() -> int {
  filterVowels(std::cin, std::cout);
}
```

- **Initializer does not need to be sorted**
- **`s.contains(x)` as quick check if x is present in `std::set`**
  - Discouraged alternatives: `s.find(x) != s.end()` or `s.count(x)`

Map of Key-Value Pairs (`std::map`)

`#include <map>`


```
std::map<char, size_t> vowels{{'a', 3}, {'e', 8}, {'i', 5}, {'o', 4}, {'u', 2}, {'y', 1}};
```

`rend()` `begin()` `rbegin()` `end()`

sorted keys	`['a']`	`['e']`	`['i']`	`['o']`	`['u']`	`['y']`
associated values	3	8	5	4	2	1

- **Stores key-value pairs in sorted order**
  - Sorted by key in ascending order
  - Order can be overwritten by the 3rd template parameter
- **Iterators access `std::pair<key, value>`**
  - Use `.first` for key and `.second` for value

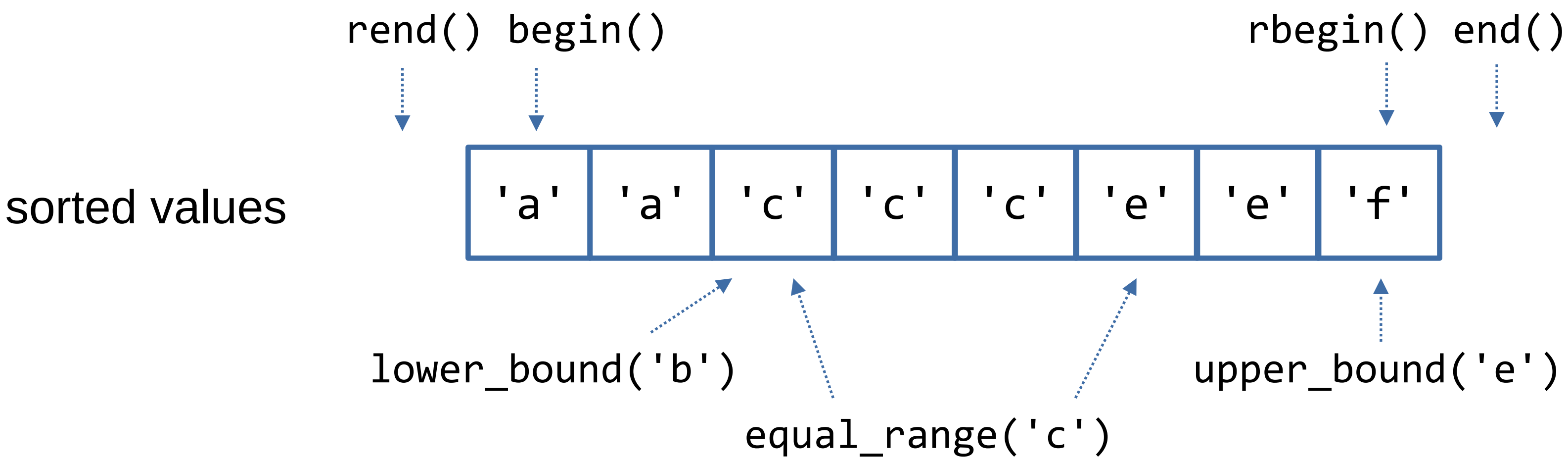
```
auto countVowels(std::istream& in, std::ostream& out) -> void {
  std::map<char, size_t> vowels{{'a', 0}, {'e', 0}, {'i', 0}, {'o', 0}, {'u', 0}, {'y', 0}};
  char c{};
  while (in >> c) {
    if (vowels.contains(c)) { // only count those chars that are already in the map
      ++vowels[c];
      for_each(cbegin(vowels), cend(vowels), [&out](auto const& entry) {
        // entry is a pair<char, size_t>
        out << entry.first << " = "<< entry.second << '\n';
      });
    }
  }
}
```

- **`m.contains(x)` as quick check if x is a key present in `std::map`**
  - Discouraged alternative: `m.find(x) != m.end()` or `m.count(x)`
- **`auto` is simpler than `std::pair<key, value>`**

```
auto countStrings(std::istream& in, std::ostream& out) -> void {
  std::map<std::string, size_t> occurrences{};
  std::istream_iterator<std::string> inputBegin{in};
  std::istream_iterator<std::string> inputEnd{};
  for_each(inputBegin, inputEnd, [&occurrences](auto const & str) {
    ++occurrences[str];
  });
  for(auto const & occurrence : occurrences) {
    out << occurrence.first << " = "<< occurrence.second << '\n';
  }
}
```

- **Indexing operator[ ] inserts a new entry automatically if key is not present**
  - Key is the argument of the index operator, values is the default value of the value type
  - Returns the value by reference, which allows modification

```
std::multiset<char> letters{'a', 'a', 'c', 'c', 'c', 'e', 'e', 'f'};
```



- **Multiple equivalent keys allowed**
  - Use `equal_range()` or `lower_bound()/upper_bound()` member functions/algorithms to find boundaries of equivalent keys
- **Can be a bit more tedious to work with than `std::set`**

Example: `std::multiset` (Sorted Word List)

`#include <set>`

```
auto sortedStringList(std::istream& in, std::ostream& out) -> void {
  using inIter = std::istream_iterator<std::string>;
  using outIter = std::ostream_iterator<std::string>;
  std::multiset<std::string> words{inIter{in}, inIter{}};
  copy(cbegin(words), cend(words), outIter(out, "\n"));
  auto current = cbegin(words);
  while (current != cend(words)) {
    auto endOfRange = words.upper_bound(*current);
    copy(current, endOfRange, outIter{out, ", "});
    out << '\n'; // next range on new line
    current = endOfRange;
  }
}
```

- **First copy-algorithm call prints each word on a separate line**
- **Code in `while`-loop groups equivalent words on one line**

?

<pre>#include <map>
#include <string>
 	
std::map<double, std::string> const names {
  { 0.0, "zero"},
  { 1.0 / 0.0, "inifinity"},
  {-1.0 / 0.0, "-infinity"},
  { 0.0 / 0.0, "NaN"}
};</pre>
	Incorrect
	
	The `NaN` value breaks the ordering of the keys, because all comparison operations return `false`.

<pre>#include <algorithm>
#include <set>
 	
auto incrementAll(std::set<int>& values) -> void {
  for_each(begin(values), end(values),
           [](int& element) {
    ++element;
  });
}</pre>
	Incorrect
	
	Elements in an `std::set` (or keys in an `std::map`) must not be modified from outside. This might break the invariant that the elements are ordered. There is no means of recognizing such a modification when an element was modified through an iterator (or any other reference of that element)

Hashed Containers

Goals:

- You know the different hashed containers of the standard library
- You know the capabilities of the individual hashed containers

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- **C++11 introduced associative containers using hashing**
  - More efficient lookup
  - No sorting
- **Standard lacks feature for creating your own hash functions**
  - `std::hash<T>` functor for library types and built-in types provided, esp. `std::string`
- **DIY programming of hash functions is hard and prone to failure, i.e. it might produce too many collisions -> stick to standard types, like `std::string` for keys**

Example: `std::unordered_set`

`#include <unordered_set>`


```
#include <algorithm>
#include <iostream>
#include <iterator>
#include <unordered_set>

auto main() -> int {
  std::unordered_set<char> const vowels{'a', 'e', 'i', 'o', 'u'};
  using in = std::istreambuf_iterator<char>;
  using out = std::ostreambuf_iterator<char>;
  remove_copy_if(in{std::cin}, in{}, out{std::cout},
    [&](char c) { return vowels.contains(c); }
  );
}
```

- **Usage is almost equivalent to `std::set`**
  - Except for the lack of ordering
- **Don't use `std::unordered_set` with your own types, unless you are an expert in hash functions and you benefit from the speedup**
  - Boost library provides hash-combiner helper

```
#include <iostream>
#include <string>
#include <unordered_map>

auto main() -> int {
  std::unordered_map<std::string, int> words{};
  std::string s{};
  while (std::cin >> s) { ++words[s]; }
  for(auto const& p : words) {
    std::cout << p.first << " = "<< p.second << '\n';
  }
}
```

- **Usage is almost equivalent to `std::map`**
  - Except for the lack of ordering
- **Don't use `std::unordered_map` with your own types, unless you are an expert in hash functions and you benefit from the speedup**
  - Boost library provides hash-combiner helper

Iterators

Goals:

- You know the different iterator categories and their capabilities
- You can explain the difference between a const iterator and a const_iterator

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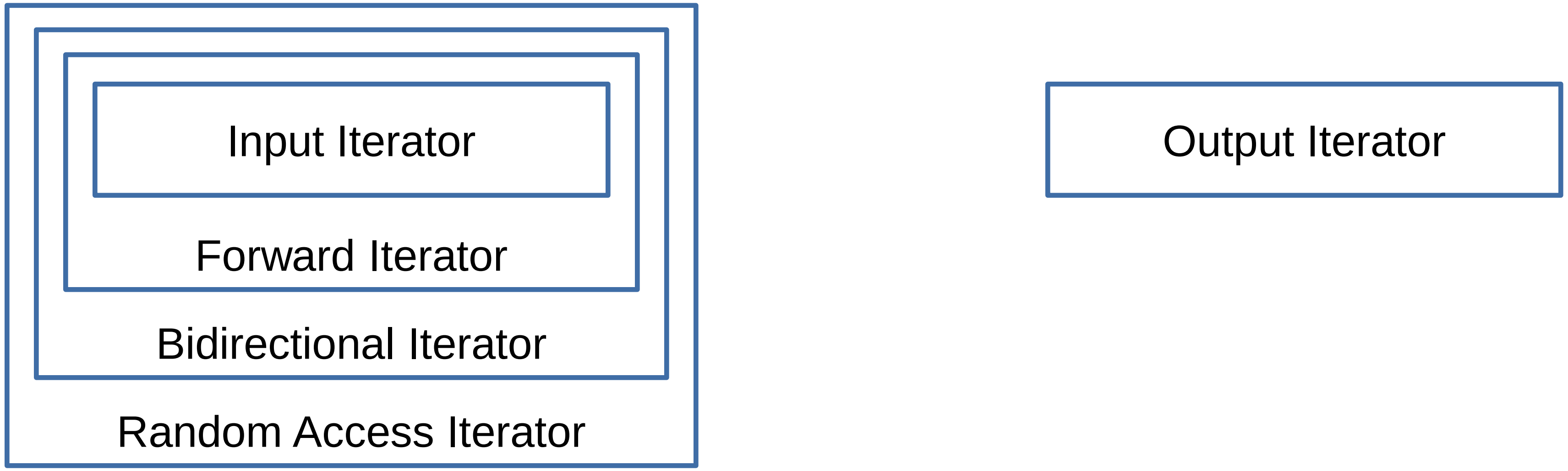
STL Iterator Categories



- **Different containers support iterators of different capabilities**
- **Categories are formed around increasing "power"**
  - `std::input_iterator` corresponds to istream_iterator's capabilities
  - `std::ostream_iterator` is an output_iterator
  - `std::vector<T>` provides random_access iterators

- **Supports reading the "current" element (of type `Element`)**
- **Allows for one-pass input algorithms**
  - Cannot step backwards
- **Models the std::istream_iterator and std::istream**
- **Can be compared with == and `!=`**
  - To other iterator objects of the same type: `It`
- **Can be copied**
  - After increment (calling ++) all other copies are invalid!
  - `*it++` is allowed explicitly (by the standard)

```
struct input_iterator_tag{};

auto operator* () -> Element;
auto operator++() -> It&;
auto operator++(int) -> It;
auto operator==(It const&) -> bool;
auto operator!=(It const&) -> bool;
auto operator= (It const&) -> It&;
It(It const&); //copy ctor
```

- **Can do whatever an input iterator can, plus...**
  - Supports changing the "current" element (of type `Element`)
    - Unless the container or its elements are const
- **Still allows only for one-pass input algorithms**
  - Cannot step backwards
  - But can keep iterator copy around for later reference
- **Models the `std::forward_list` iterators**

```
struct forward_iterator_tag{};

auto operator* () -> Element&;
auto operator++() -> It&;
auto operator++(int) -> It;
auto operator==(It const&) -> bool;
auto operator!=(It const&) -> bool;
auto operator= (It const&) -> It&;
It(It const&); //copy ctor
```

- **Can do whatever a forward iterator can, plus...**
  - Can go backwards
- **Allows for forward-backward-pass algorithms**
- **Models the `std::set` iterators**

```
struct bidirectional_iterator_tag{};

auto operator* () -> Element&;
auto operator++() -> It&;
auto operator++(int) -> It;
auto operator--() -> It&;
auto operator--(int) -> It;
auto operator==(It const&) -> bool;
auto operator!=(It const&) -> bool;
auto operator= (It const&) -> It&;
It(It const&); //copy ctor
```

- **Can do whatever a bidirectional iterator can, plus...**
  - Directly access element at index (offset to current position): distance can be positive or negative
  - Go n steps forward or backward
  - "Subtact" two iterators to get the distance
  - Compare with relational operators (<, <=, >, >=)
- **Allows random access in algorithms**
- **Models the `std::vector` iterators**

```
struct random_access_iterator_tag{};

auto operator* () -> Element&;
auto operator++() -> It&;
auto operator++(int) -> It;
auto operator--() -> It&;
auto operator--(int) -> It;
auto operator==(It const&) -> bool;
auto operator!=(It const&) -> bool;
auto operator= (It const&) -> It&;
It(It const&); //copy ctor

auto operator[](distance) -> Element&;
auto operator+(distance) -> It;
auto operator+=(distance) -> It&;
auto operator-(distance) -> It;
auto operator-=(distance) -> It&;
auto operator-(It const &) -> distance;
//relational operators, like <
```

- **Can write value to current element, but only once (*it = value)**
  - Then increment is required
- **Modeled after std::ostream_iterator**
- **Most other iterators can also act as output iterators**
  - Unless the underlying container is const
- **Exception: associative containers allow only read-only iteration**
- **No comparison and end to an out range is not queryable**

```
struct output_iterator_tag{};

auto operator*() -> Element&;
auto operator++() -> It&;
auto operator++(int) -> It;
```

What Are These Iterator Categories For?


```
template<class InputIt, class OutputIt>
auto copy(InputIt first, InputIt last, OutputIt result) -> OutputIt;

template<class RandomAccessIterator>
void sort(RandomAccessIterator first, RandomAccessIterator last);
```

- **Some algorithms only work with powerful iterators, e.g. `std::sort()` requires a pair of random access iterators (it needs to jump forward and backward)**
- **Some algorithms can be implemented better with more powerful iterators**
  E.g. `std::advance()` or `std::distance()`
- **Categories are enforcable with C++20 concepts**

```
std::distance(start, goal);
std::advance(itr, n);
```

- **`std::distance()` counts the number of "hops" iterator `start` must make until it reaches `goal`**
  - Efficient for random access iterators
  - For other iterators the algorithm has to loop
    - This implies that `goal` has to be "after" `start`. I.e. reachable by an arbitrary number of ++ calls
- **`std::advance()` lets `itr` "hop" `n` times**
  - Efficient for random access iterators
  - For other iterators the algorithm it has to loop
  - Allows negative `n` for bidirectional iterators

std::advance vs std::next

```
auto main() -> int {
  std::vector primes{2, 3, 5, 7, 11, 13};

  auto current = std::begin(primes);
  auto afterNext = std::next(current);
  std::cout << "current: " << *current << " afterNext: " << *afterNext << '\n';

  std::advance(current, 1);
  std::cout << "current: " << *current << " afterNext: " << *afterNext << '\n';
}
```

- **`std::next / std::prev`**
  - Has a default step of size 1, can be specified
  - Makes a copy of the argument
  - Argument can be a temporary
- **`std::advance`**
  - Requires a step
  - Modifies the argument iterator
  - Returns void

```
std::vector v{3, 1, 4, 1, 5, 9, 2, 6};
for (auto it = cbegin(v); it != cend(v); ++it) {
  std::cout << *it << " is " << ((*it % 2) ? "odd" : "even") << '\n';
}
```

- **Use auto**
  - because `begin()`'s return type is often long (pre C++11 see below)
- **Use `begin()` and `end()` if you intend to change elements**
  - Otherwise `cbegin()` and `cend()`

```
for (std::vector<int>::const_reverse_iterator crit = crbegin(v);
     crit != crend(v); ++crit) {
  std::cout << *crit << ", ";
}
```

- **Declaring an iterator `const` would not allow modifying the iterator object**
  - You cannot call ++
- **`cbegin()` and `cend()` return const_iterators**
  - This does NOT imply the iterator to be `const`
  - The elements the iterator walks over are `const`

```
std::vector v{3, 1, 4, 1, 5, 9, 2, 6};

auto const iter1 = values.begin(); //std::vector<int>::iterator const
++iter1;

auto iter2 = values.cbegin(); //std::vector<int>::const_iterator
*iter = 2;
```

?

`using InIter = std::istreambuf_iterator<char>;`
`void last(std::istream& in) -> std::optional<char> {`
`  InIter current{in}, eof{}, previous{};`
`  while (current != eof) {`
`    previous = current++;`
`  };`
`  if (previous != eof) {`
`    return *previous;`
`  }`
`  return{};`
`}`
	Incorrect
	
	Beware! This compiles and might work as expected, but is not guaranteed! However, after an input iterator has been incremented, its copies are invalidated!

`auto median(std::vector<int>& values) -> int {`
`  if (values.empty()) {`
`    throw std::invalid_argument{"empty..."};`
`  }`
`  sort(begin(values), end(values));`
`  return values[values.size() / 2];`
`}`
	Correct
	
	With an std::vector this example is correct. A vector provides random access iterators. Only random access iterators can be used with std::sort and they provide index access with [].

- **The standard library provides the most needed data structures**
  - All work very similar with algorithms, as they have a similar API and provide iterators
  - Learn where to apply more efficient member functions instead of algorithms
    - E.g. `std::set::count()` member function vs. `std::count()` algorithm
- **Understand where to apply which data structure**
- **Iterators have different capabilities and provide corresponding member operators**

Changes Since HS21

- **Adapt function signatures to trailing-return types**
- **Introduction of .contains()**